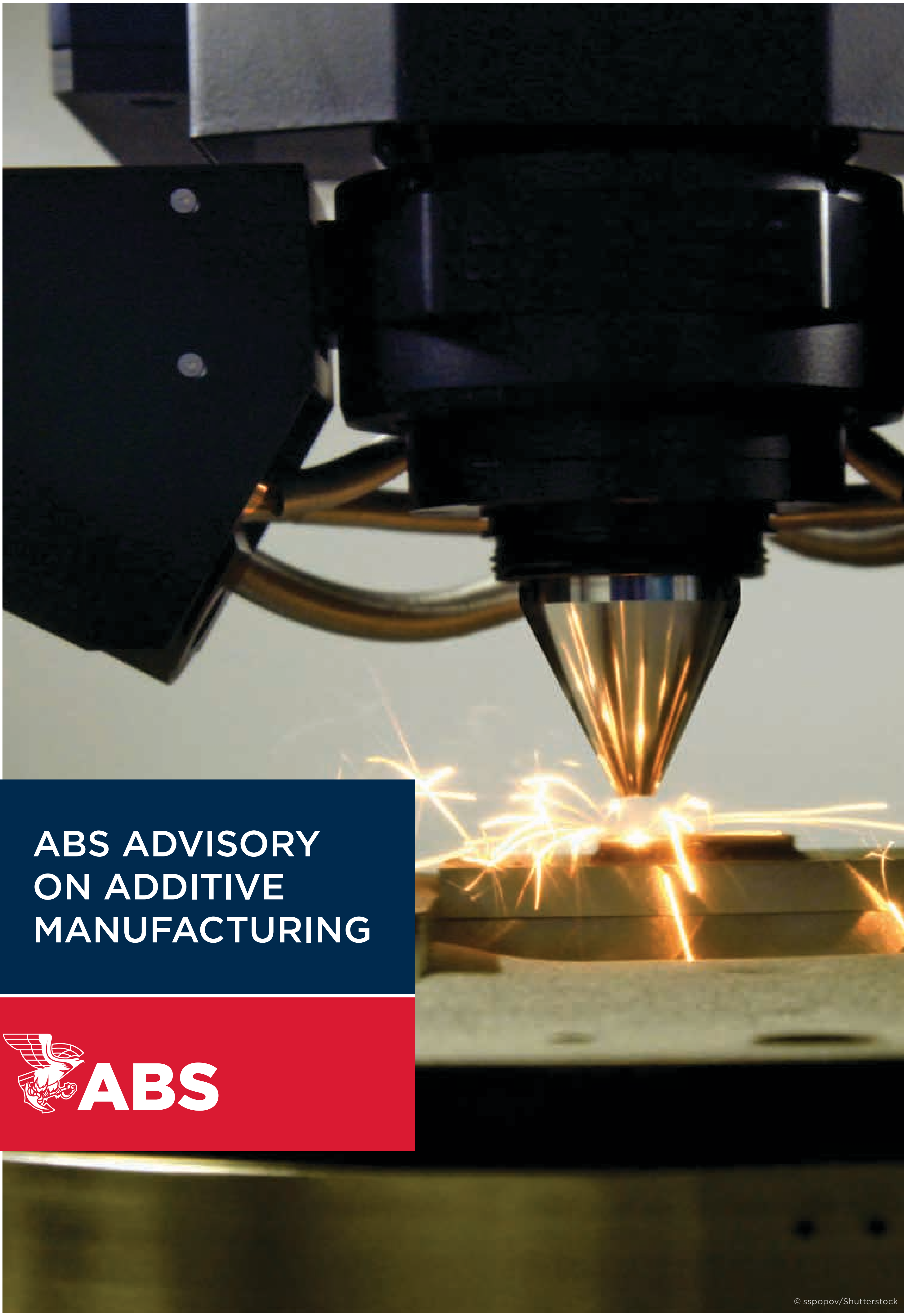

ABS ADVISORY ON ADDITIVE MANUFACTURING

MISSION

The mission of ABS is to serve the public interest as well as the needs of our members and clients by promoting the security of life and property and preserving the natural environment.

HEALTH, SAFETY, QUALITY AND ENVIRONMENTAL POLICY

We will respond to the needs of our members, clients and the public by delivering quality service in support of our Mission that provides for the safety of life and property and the preservation of the marine environment.

We are committed to continually improving the effectiveness of our HSQE performance and management system with the goal of preventing injury, ill health and pollution.

We will comply with all applicable legal requirements as well as any additional requirements ABS subscribes to which relate to HSQE aspects, objectives and targets.

ADVISORY NOTICE

The intent of publishing this Advisory on Additive Manufacturing is to inform and to collect feedback from industry during its use to be able to develop guidance in the future. For additional information, please contact ABS Technology.

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ADDITIVE MANUFACTURING ADVISORY

1 INTRODUCTION

The latest innovation in manufacturing, additive manufacturing (AM), is the fabrication of a part by adding material layer by layer. AM technologies can reshape the way parts are designed and constructed. The rapid development of this technology has indicated that the marine and offshore industries may benefit from the capability of AM to produce new or replacement parts. This advisory provides an overview of metal AM technologies, technical challenges and tradeoffs, changes to the design process, quality, reliability and the role of ABS.

Additive manufacturing is also known as 3-D printing and offers the ability to produce a low number of complex parts locally, quickly and economically, relative to traditional manufacturing. AM technologies enable design features that are too expensive or impractical using traditional manufacturing techniques such as casting or forging.

Additive manufacturing typically adds the most value when parts can be categorized by one of the scenarios listed below and shown in Figure 1.

- Produce parts at the AM machine locally or in remote sites
- Produce small batches of parts, including single-run custom parts
- Produce parts rapidly, such as for repair and prototyping
- Produce complex geometries, enabling designs that combine parts to reduce the number of pieces in assemblies
- Produce parts on-demand, reducing inventory costs
- Produce parts with features that improve design functionality, like internal cooling channels

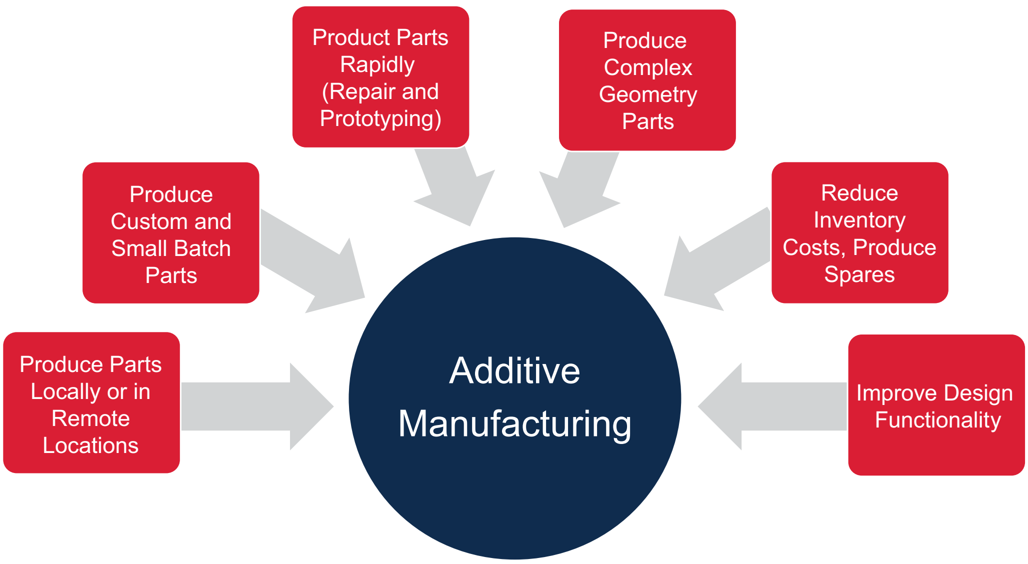

Figure 1 – Value of AM to the marine and offshore markets

Industries that currently use AM benefit the most from the ability to produce lightweight parts, single-part batches and complex geometries. The scenarios in Figure 1 could apply to many parts in the marine and offshore industries, such as the metal AM propeller shown in Figure 2. Both the context for needing the part and the design of the part (e.g., material, geometry, etc.) influence which process is most appropriate.

The American Society of Testing and Materials Committee on AM Technologies (ASTM F42) outlines seven categories of additive manufacturing. Four of these seven are capable of producing metallic parts. This advisory will focus on metal-based processes and their applications in the marine and offshore industries.

Figure 2 – Additively manufactured propeller

2 OVERVIEW OF METAL-CAPABLE AM PROCESSES

The four AM processes used to produce metallic parts are powder bed fusion (PBF), directed energy deposition (DED), binder jetting (BJ) and sheet lamination. Currently, PBF, DED and BJ are used in the aerospace, defense, automotive and medical industries to produce functional parts. Sheet lamination, although capable of producing metallic parts, is not widely used due to various constraints such as lack of process industrialization and inefficient material use. Therefore, this advisory will only address the PBF, DED and BJ processes.

Building a part follows an 8-step process, explained below.

Step 1: Define the geometry of the part by building it in computer-aided design (CAD) software and/or using a 3D scanning device.

Step 2: Convert the CAD or point cloud file into a standard tessellation language (STL) format, a common language for most commercial 3D printing machines.

Step 3: Divide the part design into thin buildable layers with a program called a slicer; send the sliced file to the machine.

Step 4: Prepare the machine before starting fabrication. This setup includes, but is not limited to, confirming building parameters and determining the material required to print the part.

Step 5: Begin the build process for the machine, which fabricates the part layer by layer. PBF, DED and BJ each produce layers differently.

Step 6: Remove the part from the AM machine. This involves removing supports, clamps and loose powder, if applicable.

Step 7: Conduct any necessary post-processing work. This may include machining, grinding, blasting and heat treatment. Post-processing work is required when parts produced in the "as fabricated" condition do not meet relevant design criteria such as dimensional tolerances and surface roughness.

Step 8: Perform nondestructive evaluation (NDE) and design testing prior to final application.

2.1 POWDER BED FUSION (PBF)

PBF forms three-dimensional parts by selectively melting thin layers of powder. Most PBF machines have four main features:

- A build chamber capable of maintaining an inert atmosphere or a vacuum
- A movable build platform capable of lowering the build one thickness layer at a time
- A powder spreading roller designed to coat the current build layer with the appropriate thickness of powder
- A fixed energy source such as a laser or electron beam and a beam controller that guides the energy

There are many possible configurations for PBF AM machines, and each has features that vary depending on the original equipment manufacturer (OEM). For instance, some OEMs make machines with electron beam sources and electromagnetic guides, while others use laser sources and mirrored guides. Some machines possess multiple energy sources and beam controllers. Figure 3 shows a typical building process for a PBF machine divided into the following three steps:

1. The powder roller distributes a layer of powder evenly over the work area of the build platform.
2. The energy source directs the beam to melt selected regions of the freshly deposited powder layer.
3. The build platform lowers by one layer thickness and the powder roller re-applies a new layer of powder.

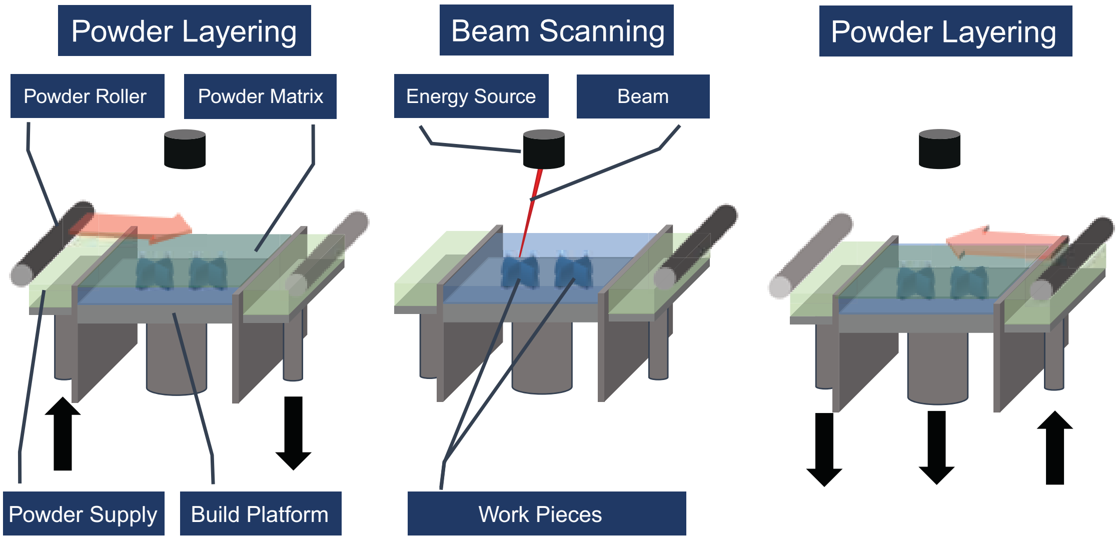

Figure 3 – Typical powder bed fusion build steps

Currently, PBF machines offer some of the best resolution available for AM parts. PBF is primarily used for smaller, low-dimensional tolerance, high-value components such as fuel nozzles and implants. For example, the National Aeronautics and Space Administration (NASA) used a PBF process to create the rocket injector shown in Figure 4. Using PBF instead of traditional manufacturing allowed NASA to reduce the number of parts in the assembly from 115 to two, as well as reduce the overall assembly time.

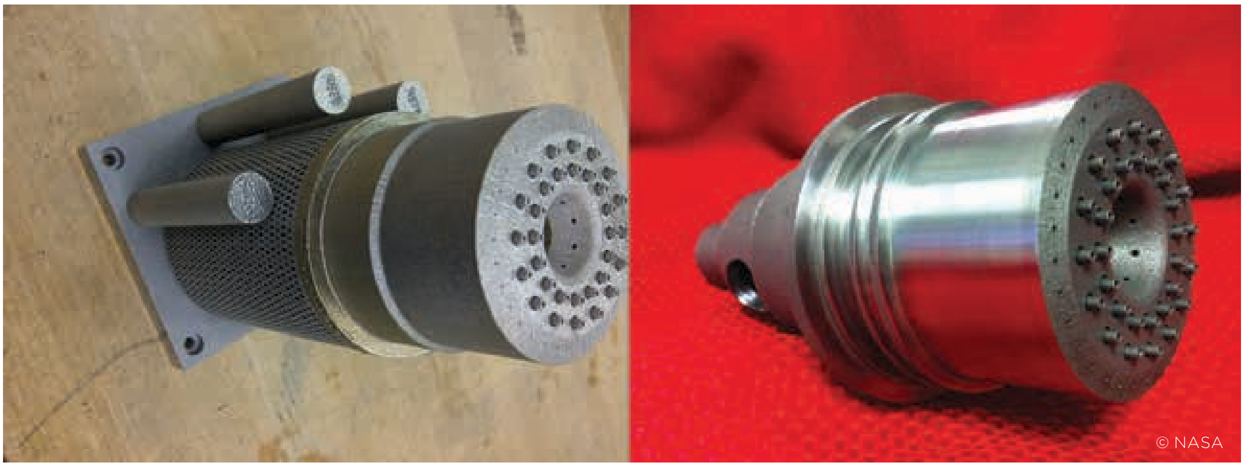

Figure 4 – NASA rocket injector, manufactured with PBF AM, reducing 115 parts to two

2.2 DIRECTED ENERGY DEPOSITION (DED)

DED refers to a set of processing methods where a directed energy source such as a laser or an electron beam creates a melt pool into which material is added. Figure 5 and Figure 6 illustrate electron beam and laser powder DED processes, respectively. In most configurations, a multi-axis arm guides a deposition head along a planned tool path. It is also common for the build platform to be able to move during construction for additional deposition flexibility. DED methods can add material to existing parts or build new parts. Common DED techniques include wire-fed laser automated welding, gas tungsten arc (GTA) automated welding, gas metal arc (GMA) automated welding and blown powder deposition.

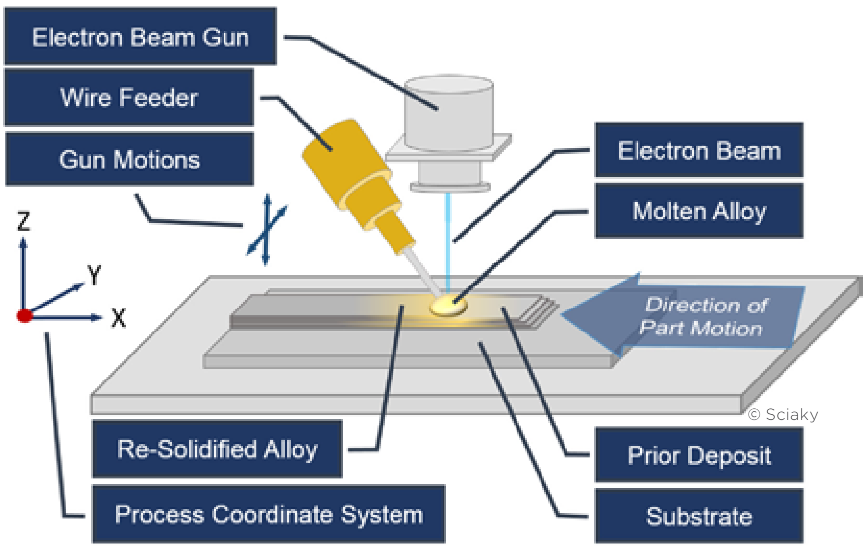

Figure 5 – Electron beam DED Illustration

A DED multi-axis arm configuration often includes both the energy source and the material supply feed(s). Where PBF focuses on small, high-accuracy parts, DED produces larger parts in close-to-final "near-net" shape. DED is capable of depositing a larger amount of metal in a shorter time than other AM methods. Figure 7 illustrates a Sciaky electron-beam deposition head with dual wire feeds and a near-net shape part on the build platform.

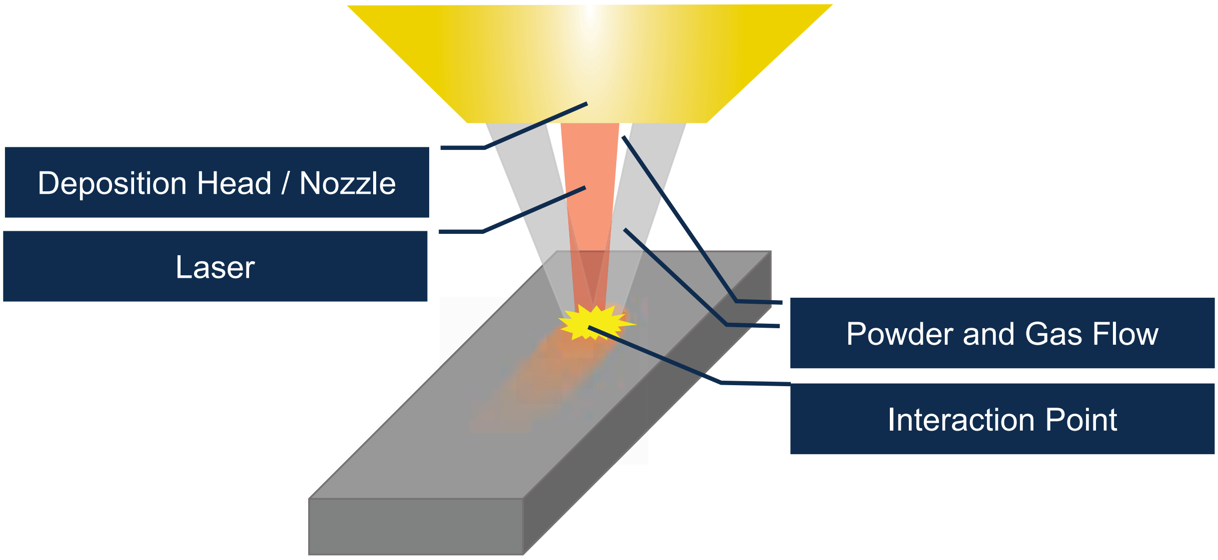

Figure 6 – Laser blown powder DED

The required atmosphere for the build changes depending on the type of energy source used. As with PBF, electron beam DED requires the build to be contained in a vacuum. However, DED methods such as GTA or GMA can function without a vacuum by using an inert gas supplied from the deposition head. DED does not require a powder rolling system, and it is flexible in the size of parts it can produce. DED systems can produce parts more than 18 feet in length and have the most scalable work envelope currently available.

Figure 7 – Electron beam DED system with near-net shape part

2.3 BINDER JETTING (BJ)

BJ creates parts by repeatedly bonding areas of powder layers with the selective application of a binder. BJ operates similarly to PBF (see Figure 3) but uses a print head to supply a binder to join particles rather than an overhead energy source to melt them. BJ is unique in metallic AM in that the binding process does not melt the printed particles. Figure 8 depicts a printer head applying binder to a loose layer of powder to form a set of parts.

Figure 8 – Binder jet metal printing

BJ can produce metallic parts directly or indirectly. Both the direct and indirect printing operations proceed in ambient atmosphere at room temperature. BJ produces metallic parts directly with a two-step process. The first step is to print the shape of the part by applying binder to a loose bed of metallic powder layer by layer. The unbound powder in each layer serves as a support for powder bound in subsequent layers.

The second step is the curing and sintering process. When printing completes, the box of loose and bound powder is transferred into a curing oven. While inside, the heat solidifies the binder enough that the bound part can be handled without the loose powder supporting it. When curing finishes, the bound part is removed from the box, separated from the loose powder and transferred into a sintering oven. The part then undergoes operations such as sintering, infiltration, and hot-isostatic-pressing (hipping) before use. An example of a directly produced stator for downhole oilfield applications is shown in Figure 9. A stator made with traditional machining costs around $400 or $500, but can be fabricated with AM for less than $200 each.

Figure 9 – Metal powder BJ stator

BJ indirectly produces metallic parts by printing the sand molds used in traditional casting operations, shown in the propeller casting in Figure 10a and Figure 10b. BJ produces complex molds and cores in less time and cost than traditional methods. The propeller pattern required several months to produce traditionally, but using BJ that time was reduced to less than a week. Large parts require printing multiple molds that are produced in sections and fitted together for casting. For example, the casting displayed in Figure 10b was produced using two of the 3D printed molds shown in Figure 10a.

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Figure 10a (left) and 10b (right) – Sand binder jetting process for metal casting

The three AM processes described above are fundamentally different. Each has adequate maturity for potential cross-industry applications in the marine and offshore markets, but as with traditional manufacturing, there are challenges and tradeoffs.

3 CHALLENGES AND TRADEOFFS

The most appropriate AM process depends on the part and its context, including material, part size, design complexity, cost of energy, delivery time, post-processing requirements, transportation costs and availability of skilled labor. In general, AM can reduce production costs and lead-time with efficient, small-batch manufacturing of complex or unique metal parts. The per-unit cost of AM parts is normally higher than traditionally produced ones. However, AM provides value when the full context for the part demand is considered. Such factors could include the need to produce a part rapidly to save perishable cargo, continue oil production or reduce warehousing and transportation costs. Because the value of such external factors varies, the benefit of AM to the marine and offshore markets is best determined on a case-by-case basis.

3.1 OVERVIEW

Among AM processes there are common tradeoffs, such as between deposition speed and accuracy. Faster processes tend to deposit material less precisely. This causes parts to have wavy or rough surface finishes in the as-fabricated condition that is referred to as the "near-net" shape, which is described more in Section 3.2. Building rates also vary among different AM systems. For example, DED systems can deposit from 3-9 kg/hour, whereas PBF systems operate at less than 1 kg/hour[1]. PBF systems tend to have the smallest build volumes, whereas BJ and DED have larger volumes by comparison.

[1] Concept Laser's X Line 2000R Machine is capable of printing up to 120cm3/hour. The densest material listed in the 2000R's technical data brochure is Inconel 718, with ~8.19g/cm3. This yields a maximum kg/hour print rate of ~983g/hour. For comparison, Sciaky's EBAM systems can deposit from 3-9 kg/hour.

AM processes are variable-intensive; there can be more than 100 quality-influencing variables in a single build. This causes uncertainty in the final physical and chemical properties of parts. A part can be produced from the same machine with the same design file multiple times and the parts will not be the same.

Material properties of the feedstock and the built part contribute to this variability. Feedstock characteristics include chemical uniformity, physical uniformity and in the case of metal powders, recycling. Recycled powder has a different composition and morphology than new powder, and it may have an effect on part properties. Part properties include microstructural anisotropy, residual stress, surface roughness and defect distribution and morphology. If not managed carefully, these effects can lead to inconsistent parts and early failure.

Each of the three highlighted processes has different capabilities for dimensional tolerance, part size and complexity relative to one another, outlined generally:

- Powder Bed Fusion (PBF)
  - Tight dimensional tolerances
  - Small build volumes
  - Slow deposition speeds
  - Smooth surface finishes
  - Cannot perform repair work
  - Cannot add material to existing parts
  - Used for small, intricate components
- Directed Energy Deposition (DED)
  - Wider dimensional tolerance than PBF
  - Larger build volumes than PBF
  - Faster deposition speeds than PBF
  - Less intricate components than PBF
  - Used for medium to large parts and repair
  - Able to vary composition of the powder and wire feeds during build
- Binder Jetting (BJ)
  - Direct metal production (DMP) and indirect metal production (IMP)
  - Fabrication speed, tolerance and surface finish intermediate of PBF and DED
  - Fabrication speed varies with material and part geometry
  - IMP BJ requires a casting facility to complete part fabrication
  - Used for a wide range of small to large parts with varying complexity

3.2 NEAR-NET SHAPE

The term "near-net" describes the rough or uneven surface of parts that are close to final dimensions but may still require machining or surface treatment to meet design tolerances. Removing this roughness adds to part expense and production time. Figure 11 shows an example of surface roughness caused by two contributing factors: layer roughness and metallic particles adhered to the surface.

Layer roughness is caused from the step-like profile created during layer-by-layer melting and resolidification of material. Adhered metallic surface particles are sometimes called "satellites," and can occur in PBF when the part surface temperature is high enough to sinter surrounding powder. In direct metal printing (DMP) BJ processes, the near-net shape refers to the rough surfaces caused by excess metallic powder particles remaining after curing and sintering operations. In indirect metal printing (IMP) BJ processes, the near-net shape refers to the surface roughness that is typical of sand castings created in foundries. The overall amount of roughness varies with the layer thickness, deposition rate, type of process, etc.

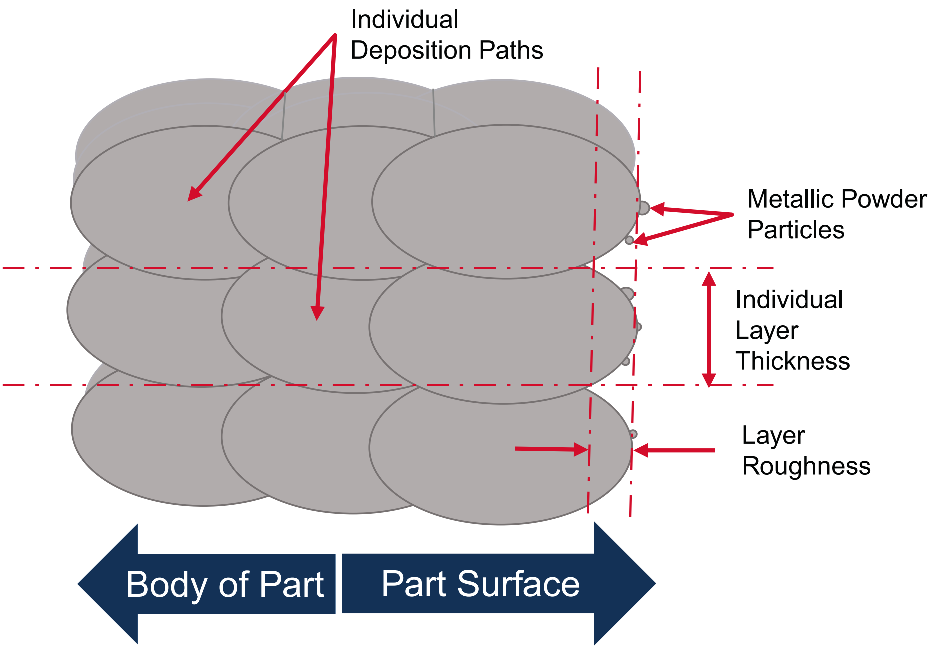

Figure 11 – Cross-section profile of a metal AM part, demonstrating surface roughness from two sources: Layer roughness and from metallic particles adhered to the surface

Near-net surfaces do not always require finishing. Figure 12 shows a ballast tank made with a Sciaky DED process that did not require machining at all locations. The upper portion of the tank was machined while the middle portion was left in near-net condition to decrease cost and save time. DED parts can require machining on the order of millimeters to centimeters to create a finished product. PBF parts require more refined finishing techniques, whereby material is removed on the order of micrometers to millimeters.

Figure 12 – Titanium ballast tank produced with Sciaky's EBAM system, showing final use of near-net shape part

3.3 CHOICE OF AM PROCESS

The choice of which AM process to use depends on the design needs for the application. In general, PBF is beneficial if the goal is to produce a small and intricate part, such as the fuel injector shown in Figure 4 or a medical implant, when machining costs are relatively high due to the increased number of machining steps. DED is beneficial if the goal is to produce a large part such as a fuel tank or structural stiffener, where the final machining is less intricate and refined. DMP BJ processes are used for small to medium components with tight tolerances, such as the stator in Figure 9. IMP BJ processes are used to print large molds for castings, such as the propeller mold in Figure 10a.

4 DESIGN PROCESS

AM is often portrayed as providing "complexity for free" by featuring structures such as the metal lattice shown in Figure 13. Although AM enables the production of complex parts, adding complexity into designs increases the time, difficulty and cost of verification, validation, risk analysis and inspection throughout the design process.

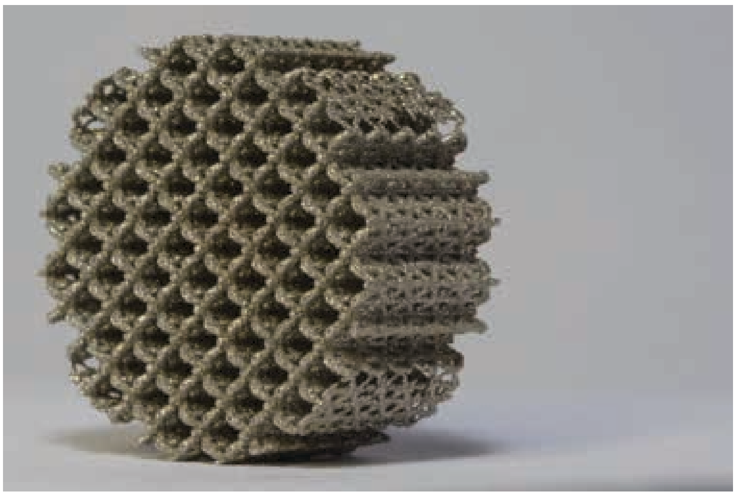

Figure 13 – Complex metal AM lattice

4.1 VERIFICATION, VALIDATION AND RISK

Figure 14 portrays a flowchart of a typical design process. The design process begins by developing the functional design specifications (FDS) for a part. The FDS quantitatively describe the expected behavior of a part and define the manner in which it will operate. Once the FDS are established, the technical design specifications (TDS) can be listed. The TDS define the manner in which the part will fulfill the FDS. When the FDS and TDS are created, certain material properties are determined. These normally include yield strength, tensile strength, hardness, impact properties, corrosion properties, etc. Once the TDS are completed, design verification, validation and risk studies begin.

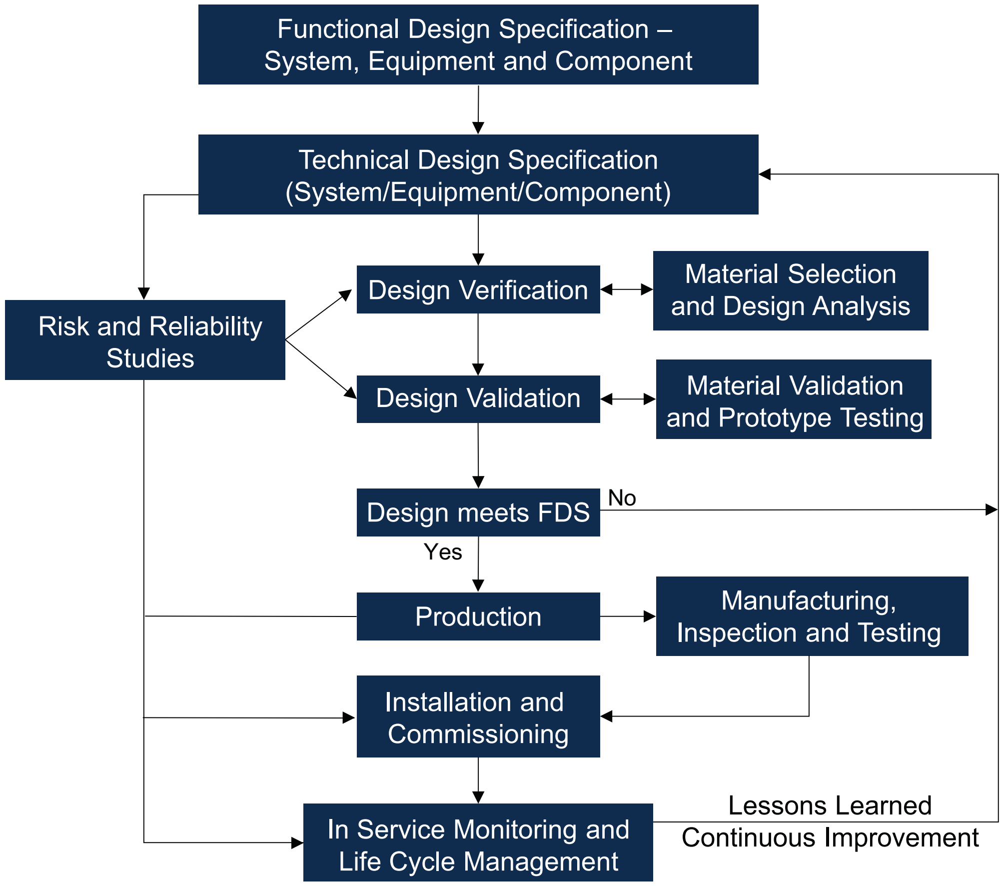

Figure 14 – General design process

Verification is the process of comparison used to determine whether the design meets the required functional and technical design specifications for all operating conditions, including material selection and design analysis. Variable material properties and complex designs make anticipating behavior in different operating conditions less accurate and reliable.

Validation is the series of performance and acceptance tests conducted to determine whether the design from the verification process reflects real-life properties accurately and precisely. Validation includes material testing, prototype testing and factory acceptance testing. Variable AM material properties complicate inference between samples and actual designs, emphasizing the importance of adequate inspection.

Risk studies are a series of analyses and workshops, such as failure mode effect criticality analysis, and are conducted to help verify that a design functions in the anticipated operating conditions to a satisfactory level of risk throughout its operational life. The quality and reliability of the design process depends on confirming that all potentially dangerous operational cases are considered. Increasing complexity hinders identification of potential risks to the behavior of the system. The overall goal is to identify risks early to avoid and mitigate potential problems and therefore increase reliability.

4.2 INSPECTION

The reliability of a part can be described by the amount of time between detecting a flaw and the failure of the part. Therefore, detecting flaws early in the manufacturing process increases the safety and reliability of designs. Design codes often specify the maximum allowable flaw size within parts, and selecting the appropriate nondestructive evaluation (NDE) techniques changes the minimum detectable flaw size, as well as probability of detection.

NDE qualification is based on correlations among defect size, orientation and morphology with part properties. In order to qualify AM parts, it is necessary to understand the assumptions of these correlations. For example, existing defect limits may be based on small numbers of randomly distributed defects. These correlations may not apply when many small pores are arranged in a non-uniformly distributed field, as is described with AM keyhole welding voids in Section 4.2.1. The defects may be smaller than the acceptable code limits, but since the correlation between part properties and defects is different, the assumptions of qualification should be confirmed.

Applying various NDE techniques depends on the material, part design and fabrication process. This is especially true for complex parts, where not all surfaces are accessible and affixing probes and determining sensor locations becomes challenging. Aspects that complicate NDE of metal AM include variable surface roughness, complex geometries, material anisotropy, small defects, chemical gradients across parts and grain structures unique to AM. Each NDE technique has strengths and weaknesses in flaw detection, and techniques are not applicable for all inspections. For example, NDE techniques such as ultrasonic testing (UT) and phased array ultrasonic testing (PAUT) are adequate at detecting planar flaws and other defect morphologies that reflect sound well, but may not be as useful for detecting small volumetric pores.

When considering which NDE techniques are adequate, it is important to understand the anticipated defect morphology. Effective inspection techniques are able to cater to AM strengths and inspect a wide range of complex part geometries. One such inspection technique is computed tomography (CT), depicted in Figure 15.

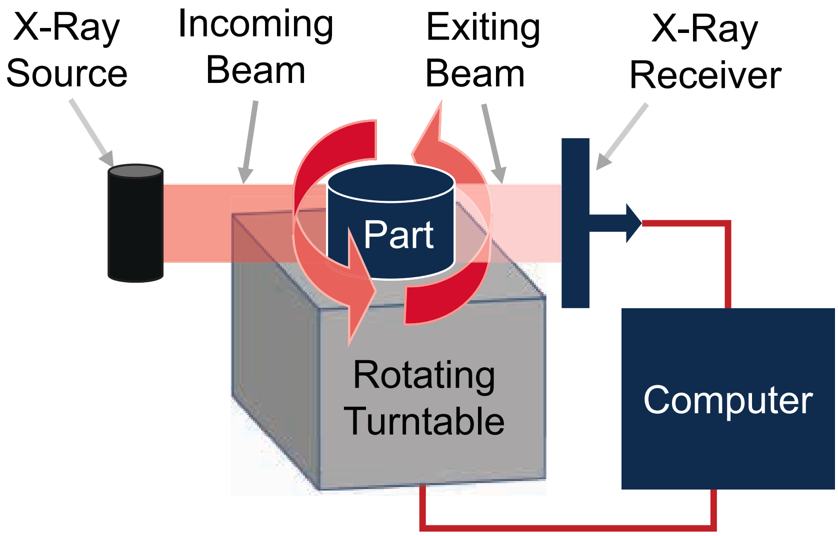

Figure 15 – Computed tomography illustration

CT is a process that is similar to radiographic testing (RT) in that it uses a radiation source to pass x-rays through a part to image its x-ray absorptivity. However, instead of taking a few images of the part at different angles, a computer system uses a rotating turntable to take many radiographic images and render a three-dimensional model. Voids are less dense than the base material, so when the beam passes through a section with a defect, such as a pore, the x-ray image for that section will exhibit a bright spot. Downsides of the process include that it is computationally and data-intensive, has a limited part inspection volume and is relatively expensive. CT is most suited to small components like PBF parts as opposed to large structural parts. Larger parts can be inspected with CT at lower resolutions; this resolution may not be adequate for qualification depending on the distribution and size of small defects within the part. Less expensive and complicated NDE techniques may be adequate if they are capable of reliably detecting the critical manufacturing defect size.

4.2.1 Defects

When examining metal AM parts for defects, it is important to note the influence of layer-by-layer construction. This is especially important for the AM processes that directly process molten metal, such as in PBF and DED. Interactions among the part geometry, material and processing plan determine the final characteristics of the part, including the defect morphology, distribution and size. For many applications, industry standards and manufacturer documentation determine acceptable tolerances, mechanical properties and acceptable flaw sizes. Common defects in metal AM include porosity, residual stress, lack of fusion, oxide and impurity inclusions, balling, cracking, warping and surface roughness.

Pores and voids can form during processing when using too much or too little power, or when travelling too quickly or slowly across the surface. For example, Figure 16 depicts a keyhole welding arrangement using a laser or electron beam source. A key feature of this type of welding scheme is its ability to create deep and narrow paths. However, if not managed properly, the scheme can create porosity by entraining gas bubbles behind the weld pool via a combination of vapor plume pressure and Marangoni currents.

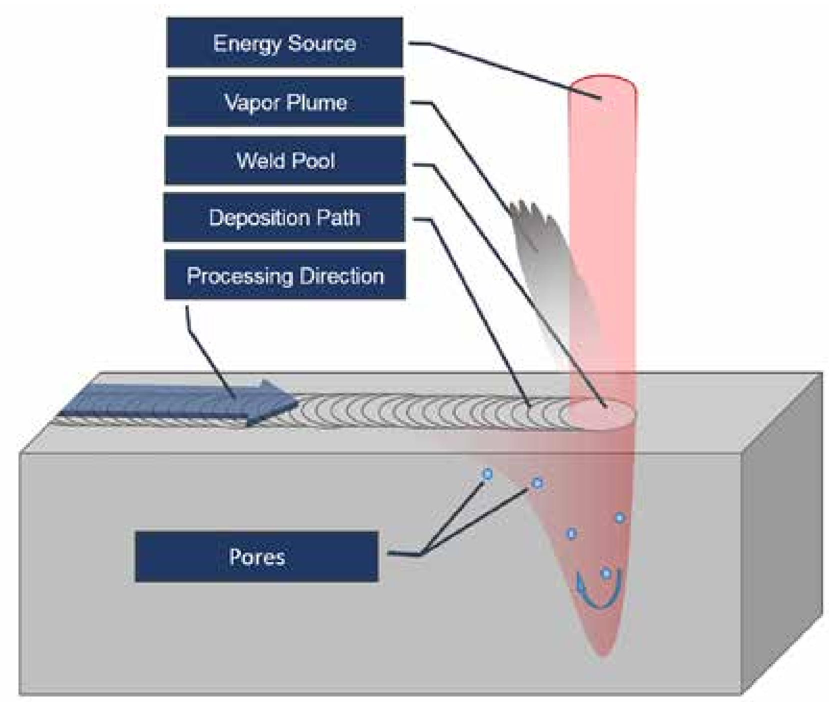

Figure 16 – Keyhole welding arrangement, showing formation of pores

The process plans for PBF and DED typically have cyclic thermal profiles due to their layer-by-layer construction, and both processes exhibit high rates of cooling. At the top layer, the metal heats, melts and solidifies. At lower layers, the metal undergoes repeated heating and cooling cycles throughout the build process. These thermal cycles can create highly anisotropic and variable microstructures, cracking and residual stresses within parts, all of which can lead to early failure.

Residual stresses can also become great enough to cause warping and separation of parts from the baseplate. If not managed or relieved, the performance of AM parts can be significantly reduced. In general, residual stresses tend to be compressive in the center of DED and PBF parts and tensile at the edges.

Residual stresses can be mitigated with processes that maintain an elevated temperature in the build volume or preheat the part during processing. This has a drawback for PBF processes because the loose powder surrounding the part has less temperature difference before melting. Increasing the temperature of the build volume and maintaining it during processing can increase surface roughness by causing adjacent powder to adhere to the surface due to heat transfer away from the edges of the part.

In general, DED and PBF are similar to complex automated welding processes. Similar to welding, managing the process temperature and thermal cycling are keys to determining final part properties and controlling defects. The metallurgical structure of AM parts differs from traditionally produced parts and exhibits anisotropy due to the layer-by-layer construction. Development and adaptation of rules, codes and standards must consider the difference in material properties and defects seen in AM parts to increase their safe and reliable use.

4.3 STANDARDIZATION

Standards facilitate business among manufacturers, purchasers, users and regulatory bodies. They increase the confidence, repeatability and comparability of products, processes and data. AM processes are variable-intensive. For example, PBF processes can have more than 100 quality-influencing variables. As the number of process variables increases, the total number of tests required to understand their relationships also increases. AM machines have user-changeable settings, but this does not mean that users always know which fundamental variables each build uses. Process variables are often grouped or hidden behind proprietary terms, and each OEM offers various quality management software that uses different metrics to monitor and control builds, such as EOSTATE, LayerQam™, CL WRX and IRISS®.

Metal AM is not widely used in high-performance applications due to a lack of mature standardization and a lack of publicly available research data for AM processing, material properties and characterization. Each proprietary development fosters the competition among metal AM technologies. However, this secrecy reduces the overall speed of technology development by forcing new users and OEMs to develop from their own experience. The information related to metal AM processes is not always comparable due to lack of knowledge of the effect of the OEMs processing and quality parameters.

Standards open the market for comparable data by reducing the knowledge barrier to entry for new users and manufacturers. Standards also expand the body of knowledge and data available to users beyond what is developed individually. Process-performance-properties data can be developed via capital investment and extensive testing, collaboration in industry or research consortia and federal investment. Therefore, developing standardization is a way to streamline metal AM processing and improve quality industry-wide.

Barriers for standardization of metal AM can be divided into four main categories: materials, process and equipment, qualification and certification and modeling and simulation, shown in Figure 17. Additional information on the structure of AM standards can be found in Appendix A.

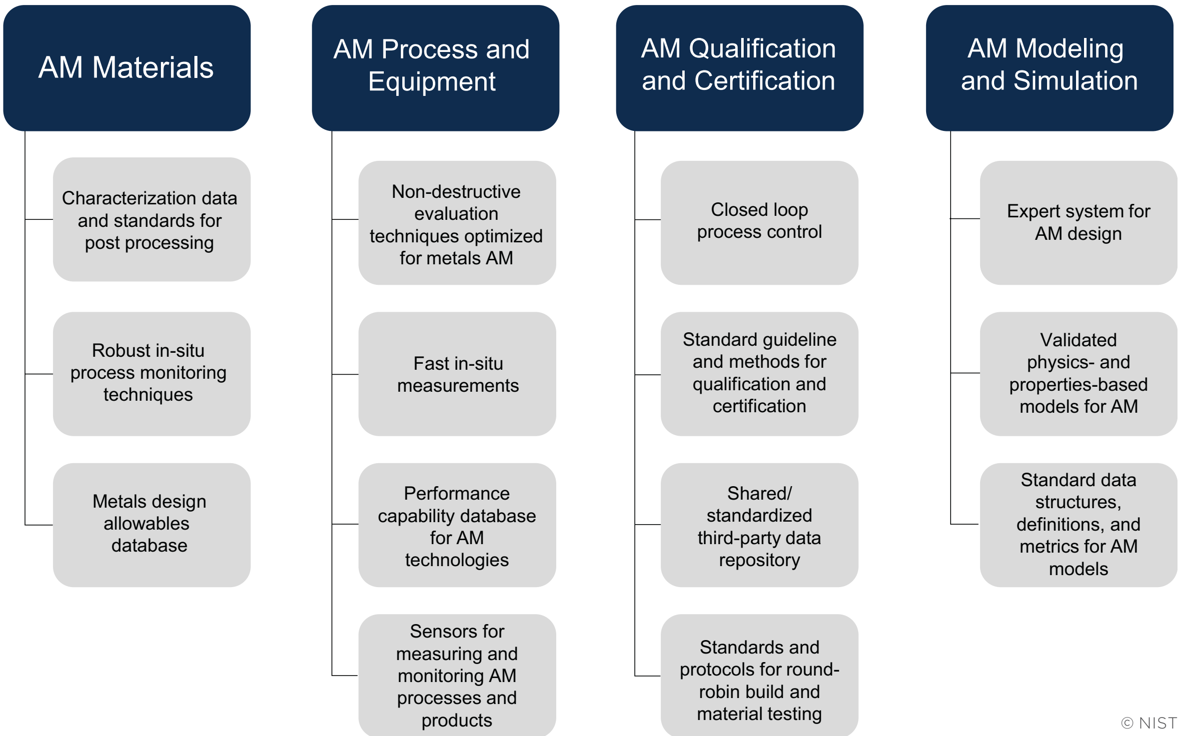

Figure 17 – Technology and measurement challenges for AM

Standardized process quality documents, such as welding procedure specifications (WPS) and procedure qualification records (PQRs), are not developed for AM technology. Standardization bodies such as ASTM F42 and AWS D20 are working to reach this goal. As standards develop and collaboration increases, the performance, reliability and quality of the AM industry will improve as a whole.

5 QUALITY

AM processes are each unique, but they also share features with well-known processes such as welding, powder metallurgy and casting. To understand quality in AM parts, it is critical to examine the relationships among the material properties, processing plan, part design and personnel training, as shown in Figure 18. Understanding quality requires viewing each of these four aspects as interdependent.

As a recap, PBF and DED processes are similar to complex automated welding. As in welding, understanding thermal history is critical to analyzing the mechanical properties and behavior of AM components. The thermal history of parts depends upon the material response to the processing, and this is determined by the processing plan for the part design. As discussed in Section 2.3, BJ produces metallic parts directly and indirectly; both make a bound powder form. For direct production, the bound metallic powder follows a workflow similar to powder metallurgy involving sintering, heat treatment, hipping, etc. For indirect production, a sand or other powder mold is produced and used directly in a traditional casting workflow.

Each AM fabrication process can be considered as a function of its inputs and outputs, as briefly outlined in Table 1.

Figure 18 – Relationship among part design, material properties, processing plan and personnel training with product quality and performance

Table 1 – AM Process Inputs and Outputs

INPUTS	OUTPUTS
• Hardware and software of AM system • Material feedstock (powder, wire, sand, binder, etc.) • Atmosphere (inert gas or vacuum, if applicable) • Design (part geometry, location of supports, etc.) • Processing plan (deposition pattern, energy distribution, material distribution, etc.)	• AM part (physical properties, chemical properties, mechanical properties) • Waste feedstock (unused powder, support structures) • Waste gas • Consumables (e.g. air filters)

5.1 PROCESSING PLAN

Designing process plans requires taking into account machine capabilities like energy source power and spot size, beam or deposition head path and the influence of quality control software, if applicable. For example, PBF and DED machine OEMs offer different options to process materials. Some OEMs make laser-PBF machines with up to four lasers working simultaneously, while others offer the ability to have two different powered lasers within the same machine. These differences should be taken into account when designing process plans for builds on different types of machines.

Materials absorb, reflect and distribute energy differently, and changing how a design is built affects its final properties. For example, if the goal were to print a cube, depositing each layer with a spiral pattern may give different properties than depositing each layer using parallel lines. Unsuitable processing plans can also cause detrimental residual stresses and defects in parts. Aspects such as powder morphology, chemistry, thermal conductivity, part geometry, build orientation, location of supports, etc., change the processing plan and final part behavior.

Therefore, the processing plan cannot be viewed separately from the part design and material properties. Controlling quality in AM processes depends on the ability to understand what occurs in the process and adjust the machine parameters and inputs in order to change the final physical and chemical properties within parts.

5.2 MATERIAL PROPERTIES

Metal AM processes predominantly use powder and wire feedstock. Metal powders are used in all three highlighted metallic AM methods in Section 2. Powder quality varies based on the manufacturing process, and is determined by particle size distribution, powder morphology, chemical composition and internal porosity. There are four main manufacturing processes used for metal AM powders: plasma atomization (PA), plasma rotating electrode process (PREP), rotary atomization (RA) and gas atomization (GA). There is a positive correlation between cost and quality of metal AM powders.

Powder features such as small particle size and distribution, spherical shape, low porosity and uniform chemistry are considered preferable. For example, PA is an expensive process with a relatively low yield compared to the other processes, but the formed powder particles are spherical and have low internal porosity. Using a smaller powder contributes to PBF part quality by allowing a user to create parts from thinner layers, and gives a smaller surface roughness profile to fabricated parts.

Powders are usually not uniform; they can contain impurities and irregularities in shape and size so will have different densities and spreading characteristics. During powder manufacturing, it is possible to form hollow particles similar to tiny metal bubbles. These hollow particles can cause defects by trapping gas within parts during processing. Obtaining accurate and precise measurements of both the physical and rheological properties of powders is therefore key to understanding powder-based AM quality.

Powders are sometimes recycled and used more than once. Between builds, used powders are sieved to remove large pieces. Recycling powders lowers production costs, but recycled powders are less spherical than virgin powders. In addition, processing changes the powder chemistry as alloys are vaporized upon heating. Research is currently underway investigating the influence of powder recycling on metal AM processes, and additional attention should be given when considering recycled powder for AM parts. Developing reliable and efficient powder recycling techniques is also key for long-term PBF AM cost effectiveness. Determining the properties of the powder used for metal AM, as well as the properties of the resulting bulk material, are necessary for industry to select powder confidently and produce consistent parts with known and predictable properties.

In contrast to powders, the welding knowledge of metal wires used for DED feedstock is more mature. Wires do not have the same issue with trapped porosity as powders, and there are some known handling and storage issues relating to wire feedstock use, including humidity, oxidation and scratching. Standardization bodies such as AWS and ASME manage quality control for welding wire consumables. Using wire feedstock for AM with automated welding processes like wire arc additive manufacturing (WAAM) may streamline material processing and certification issues because of robust existing consumable control. Each type of AM process has different material capabilities, and each OEM offers a range of materials for their machinery.

Table 3 in Appendix A outlines the material types for each of the highlighted metal AM processes. New materials are regularly developed for AM systems, and the information provided herein is only a snapshot of those currently available. A current challenge regarding material supply is that users may have to purchase feedstock directly through the respective OEMs or risk voiding the machinery warranty. As standardization, quality control and certification of AM feedstock increase, it can be anticipated that restrictive sourcing requirements will loosen.

5.3 PART DESIGN

Managing the complexity in AM design requires defining the machine capabilities and limitations. Features such as overhangs, circular channels, thin walls and other fine features may be difficult to fabricate. Different artifacts have been developed to quantify AM machine performance, but there is no single accepted design.

A single test block for all forms of metal AM is impractical due to the fundamental differences in processes. However, the National Institute of Standards and Technology (NIST) performed a review of the available test artifacts and designed one with multiple different design features that help quantify machine performance. Figure 19 shows the design for the proposed NIST test artifact, and Table 2 shows the build characteristic(s) measured by each design feature. The test artifact was tested using laser-PBF and is useful for analyzing PBF machines and processes.

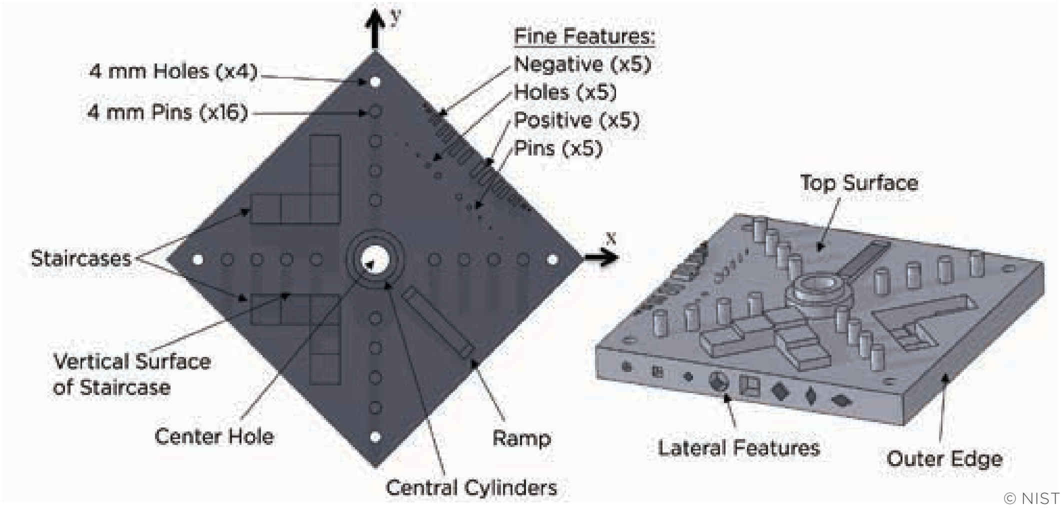

Figure 19 – NIST test artifact for PBF (Left: top view; right: oblique view)

Table 2 – Build Characteristics Measured by Each Design Feature on the NIST Test Artifact for PBF AM

Characteristics Investigated	Feature(s) Used to Demonstrate
Straight features	Vertical walls of staircases; outer edges
Parallel or perpendicular features	Vertical walls of staircases; outer edges
Circular or arced features	Center hole; central cylinders
Concentric circles or arcs	Central cylinders
Fine features	Fine features, holes and pins
3D or freeform features	Ramp; lateral features
Holes and bosses	4mm pins and holes; center holes and central cylinders; staircases; fine features
Multiple planes, overhangs	Lateral features
Location and orientation	4mm pins and holes
Geometric errors of mirror positioning axes	4mm pins and holes
Geometric errors of build platform	Staircases; center hole; ramp
Alignment errors between fabrication axes	Top surface and center hole
Errors in beam size, spot size	4mm holes and pins
Stair-stepping from PBF layers	Ramp

In addition to the characteristics listed in Table 2, the artifact can be used to analyze:

- Residual stress by measuring flatness and warping
- Surface roughness
- Metallography (micrographs, macrographs)
- Mechanical properties by machining portions of the artifact into testing specimens
- NDE response using UT, CT, etc.

The large number of different features on the artifact illustrates the difficulty in quantifying AM processes. Many different features must be examined to establish baselines and understand how changes in the machine and process affect parts. In these ways, the NIST block is useful as a broad capability demonstration and baseline for subsequent part-specific testing.

Selecting an AM machine and building parts relies on specialized knowledge of processing plans, material properties and part design. As such, reliable supply of AM products depends on the experience and training of the personnel involved.

5.4 PERSONNEL TRAINING

Reliability, safety and verifiable performance are key to the marine and offshore industries, where failure of a part in service may result in loss of life, bodily harm or damage to the environment. Displacing traditional and proven technologies with AM will take time, and early failures of AM components will have a higher impact on how the technology is perceived. Effectively trained personnel are more capable of recognizing machine errors, part defects and unsafe conditions before problems occur. AM machines are essentially small factories, as shown in Figure 20. They can have powerful lasers, electron beam sources, vacuum chambers, high-temperature surfaces and moving mechanical components. They may also use various compressed gases, as well as potentially flammable and harmful metallic feedstock. Operating AM machinery requires specialized experience, training and a well-practiced set of safety protocols.

© U.S. Navy Photo by Kaylee LaRocque

Figure 20 – DED AM system with door open for viewing

For example, PBF machines use metal powders for material feedstock. Metal powders can be flammable, can degrade when exposed to humidity and the atmosphere, and are easy to transport unintentionally. Common processes to clean and maintain the machinery include vacuuming, air blasting, brushing, etc., and it is critical to avoid exposure through inhalation or contact with eyes and other sensitive tissues. One should always wear the proper protective equipment and follow all relevant handling and workplace procedures to avoid injury to self and to others. In all cases, it should not be assumed that materials are safe for handling or for the environment. Interim guidance is included in the safety data sheets relevant to the materials used and in the machine user manual.

Operating AM machinery presents unique workplace health and safety challenges. As such, it is critical for each worker to be able to understand and anticipate workplace dangers and have the proper training to avoid, mitigate and control risks proactively. There are many different sources for training, and there is no single standardized training regimen for all processes. Accordingly, it is important to find the content relevant to the specific situation. Safety courses are offered by organizations such as America Makes and UL, universities and from the OEMs directly.

Maintaining a high level of quality products depends on increasing the knowledge available to the producer, careful observance of the design process, an awareness of fabrication inputs to outputs and operator experience and training. As AM technologies develop and costs decrease, the barrier to entry of using AM will decrease and the number of users will increase. The safe and responsible operation of AM facilities and use of AM parts in the marine and offshore industries is the goal for ABS.

6 ABS ROLE

Metal AM is a rapidly growing technology with useful implications for the marine and offshore markets. Technological development frequently exceeds the pace of standardization regulation. In these cases, existing guidance may not adequately cover the essential aspects of quality. ABS recognizes this continued need and offers guidance through the ABS *Guidance Notes on Qualifying New Technologies* (Guidance Notes). These Guidance Notes provide additional insight into the process of developing technologies, such as AM, that have no service history in their proposed application or environment by using a systems-level approach to build a framework for consistent verification and validation.

An overview of the new technology qualification process is shown in Figure 21. In general, the new technology qualification (NTQ) process is based on compliance with existing applicable rules, guides and standards, and then handling additional and special considerations through a combination of risk assessments and engineering evaluations. The qualification of technology is divided into five stages ranging from feasibility through operation and is assessed on a case-by-case basis.

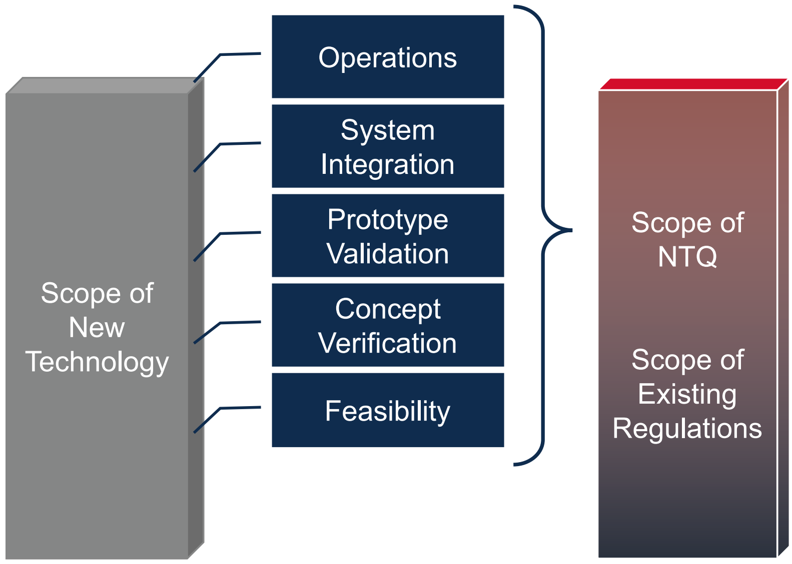

Figure 21 – New technology qualification process

The mission of ABS is to serve the public interest by promoting the security of life and property and preserving the natural environment. This mission aids in the safe and responsible growth of new technologies, and ABS looks forward to seeing how this technology will be used in the marine and offshore markets.

7 CONCLUSION

Metal AM is currently applied in the aerospace, medical, automotive and defense sectors. It has the potential to reduce production costs and lead time for the marine and offshore markets. AM can streamline the fabrication of complex and unique parts. Although metal AM provides manufacturing freedom, processes are often variable-intensive and can be difficult to control. The complexity of AM processes leads to significant part variation, indicating the need for greater knowledge of the relationships among processing plans, material properties and part design. Central to this challenge is a lack of comparable data, fundamental research and standardization.

Organizations like ASTM, AWS and ISO are working to reduce the known standardization gaps in materials, process and equipment, qualification and certification and AM modeling and simulation. Concurrently, government organizations and academic institutions are improving measurement science, process control and material property characterization. To aid in this effort, multiple AM consortia share knowledge and experience across users in different industries and backgrounds. Continued development of AM depends on collaboration among users, OEMs, academia, government and certification bodies.

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APPENDIX A

Table 3 – Material Selection for AM Processes Provided by OEMs

PBF		DED		BJ	
LASER	E-BEAM	POWDER-FED	WIRE-FED	DMP	IMP
Alloy Steels (Hot work, Maraging, Tool)	Cobalt Chrome (ASTM 75)	Aluminum (4047)	Alloy Steel (4340)	Cobalt Chrome	Ceramic Beads
Aluminum Alloys (Al-Si, Al-Mg, Al-Si-Mg)	Nickel Alloy (718)	Cobalt Chrome (Stellite 21)	Aluminum Alloys (2319, 4043)	Iron/Bronze Matrix	Chromite
Bronze	Titanium Alloys (CP, CP Grade 2, Ti6Al4V, Ti6Al4V Ell)	Nickel Alloys (625, 718)	Copper Nickel (70-30, 30-70)	Iron-Chrome-Aluminum	Silica Sand
Cobalt Chrome Alloys (Co-Cr-W, Co-Cr-Mo)		Stainless Steels (13-8, 17-4, 304, 316, 410, 420)	Nickel Alloys (625, 718)	Nickel Alloys (625, 718)	Zircon
Nickel Alloys (625, 718, Hastelloy X)		Titanium Alloys (CP Ti, Ti 6-4, Ti 6-2-4-2)	Niobium	Stainless Steels (316, 17-4, 316/Bronze Matrix, 420/ Bronze Matrix)	
Precious Metals (Gold, Silver, Platinum)		Tool Steels (H13, S7)	Stainless Steel (300 series)	Tungsten (Bonded W, WC)	
Stainless Steels (316L, 17-4PH, hot work)		Tungsten Carbide	Tantalum		
Titanium Alloys (CP, Ti6Al4V)			Titanium Alloys (CP, Ti-64)		
			Tungsten		

AM STANDARDIZATION STRUCTURE

The AM standardization structure is divided into three levels, shown in Figure 22. The top level standards address the general concepts, common requirements and safety aspects of AM processes and materials. The middle level contains process-specific and material-specific AM standards, such as material feedstock and post-processing requirements. The lowest level contains AM standards specific to the process, material and application of metal AM components. Standardization and regulation bodies, including ASTM F42, AWS D20 and ISO/TC 261, are actively working on this necessary framework.

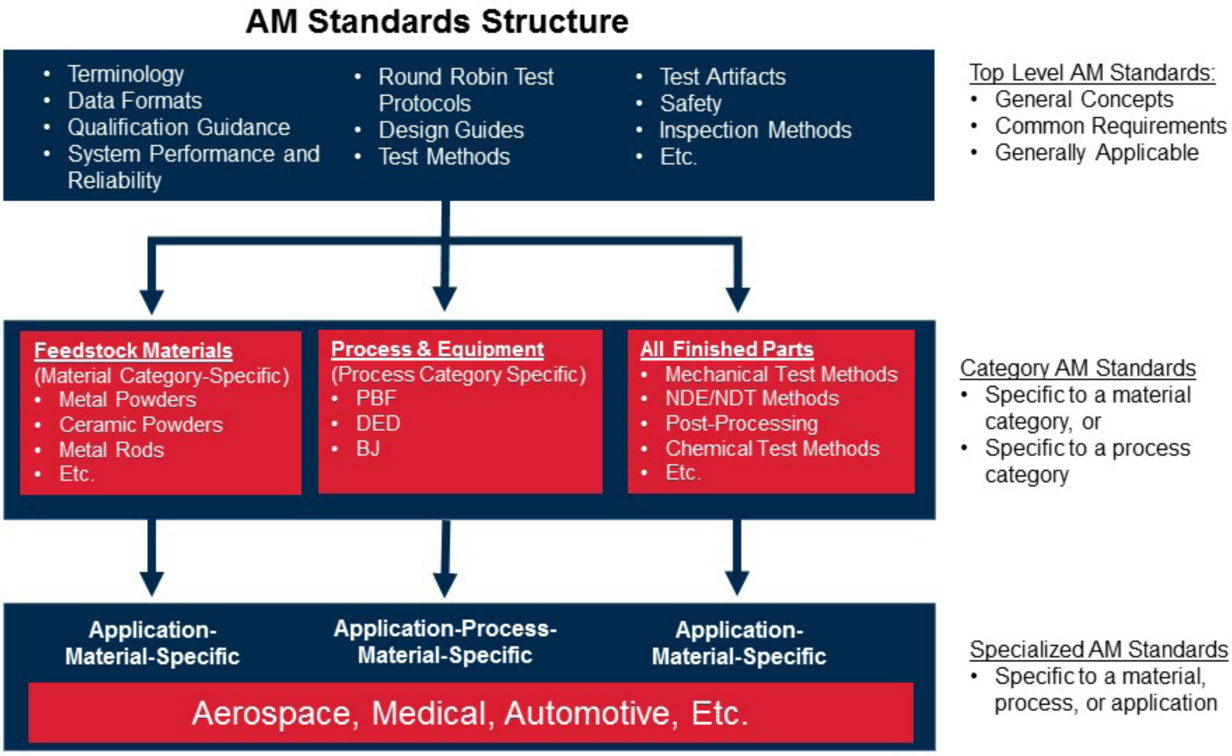

Figure 22 – AM standards structure

APPENDIX B – CASE STUDIES AND HIGHLIGHTS

LOCAL MANUFACTURING

The Port of Rotterdam opened RAMLAB, the first 3D metal printing lab for the maritime sector, in late 2016. The goal of this lab is to bring together AM machine OEMs, shipbuilders and classification societies to develop and accelerate metal AM applications in the maritime market. In 2016, the Port of Rotterdam completed a study about producing 3D-printed maritime spare parts. Potential candidates for AM parts were identified and ranked based on factors such as part consolidation, less material waste, low volume production, reduced lead times and supply chain streamlining. The study included PBF, DED and IMP BJ processes, and developed a helpful framework for selecting parts, processes and materials.

REPLACEMENT PARTS

An example of using IMP BJ for a naval military application is from the Naval Undersea Warfare Committee (NUWC). The NUWC needed to manufacture two replacement tail cones for MK 30 anti-submarine mobile targets. The cones are made of A356 aluminum, with dimensions of 22 inches by 22 inches by 22 inches.

Producing the tail cones using a traditional process of pattern-based sand casting and machining/ tooling costs $20,000 with a lead-time of 25 weeks. Printing the molds and cores using IMP BJ process from ExOne allowed the NUWC to produce the same parts for $12,600 in 10 weeks. This represents a 37 percent decrease in cost and a 60 percent reduction in time. Because a regular casting process was still used, the tail cones were able to pass traditional performance and NDE requirements.

REDUCTION IN TIME, COST AND MATERIAL

In a similar example to the ballast tank seen in Figure 12, Figure 23 shows a propellant tank created by Lockheed Martin using Sciaky's EBAM technology. Using AM allowed Lockheed Martin to reduce the cost of producing the titanium tank by 55 percent, with a 75 percent reduction in waste when compared to traditional methods. Additionally, the AM tank required 80 percent less time to fabricate. Reductions in cost, material and time were achieved due to the difficulty and expense of traditional fabrication via machining from commercially available titanium plate.

Figure 23 - Titanium propellant tank fabricated with DED technology and machining into final dimensions

The propellant tank is 16 inches in diameter. Similar tanks could be produced up to 50 inches in diameter. When the tank was pressure tested, it held 25 percent greater than nominal pressure and it burst at more than twice the nominal pressure.

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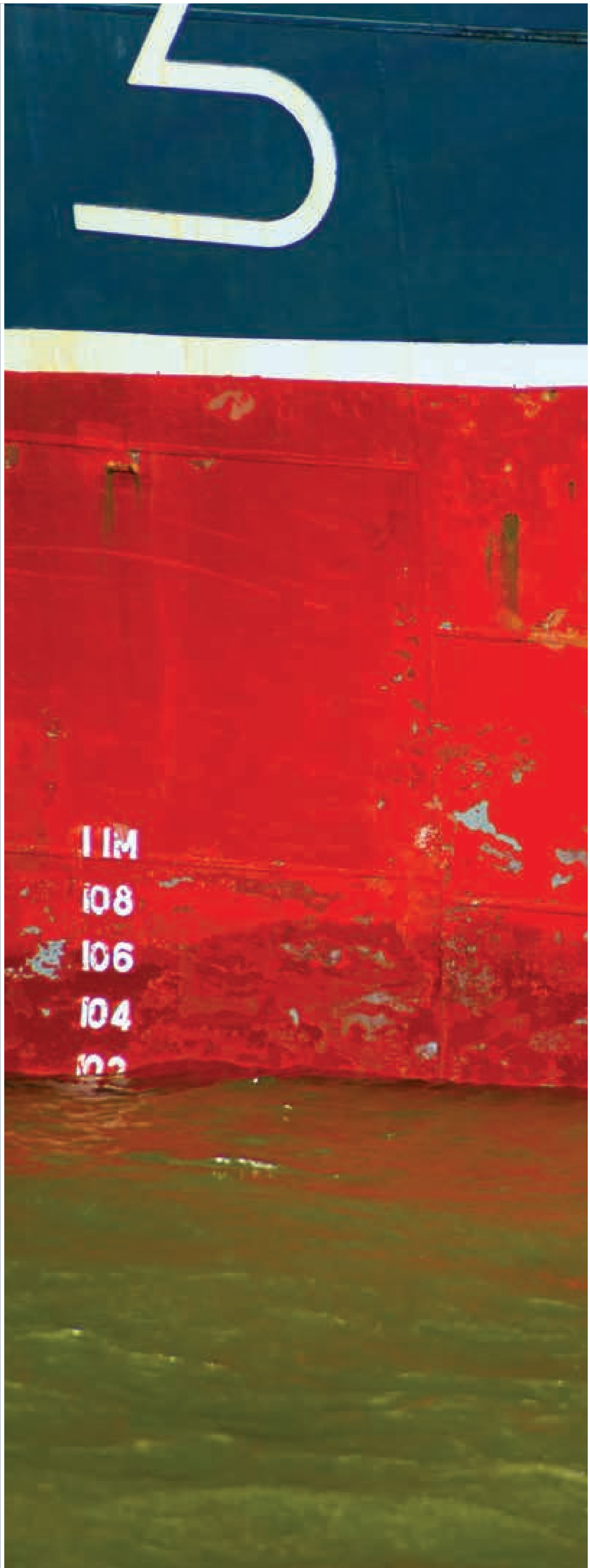

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